Response to Comment on "The Southern Ocean Biological Response to Aeolian Iron Deposition"

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Response to Comment on "The Southern Ocean Biological Response to Aeolian Iron Deposition"

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Net community production in the Southern Ocean is correlated with simulated local dust deposition, and more so with modeled deposition of soluble iron. Model simulations of the latter two properties are consistent with observations in both hemispheres. These results provide strong evidence that aerosol iron deposition is a first-order control on net community production and export production over large areas of the Southern Ocean.

Our report (*1*) integrated data over large areas of the Southern Ocean and examined the relation between observed net community production (NCP) and simulated values of the rates of both dust deposition and soluble Fe deposition by dust. Dust and soluble Fe fluxes to the sea surface were simulated using a global three-dimensional atmospheric dust transport model (*2*) that accounts for Fe solubilization in aerosols (*3*). We observed a strong covariation between NCP and local values of soluble Fe deposition, with Fe/C ratio of 2.5 μmol mol^{-1}, comparable to biological requirements. These results are consistent with aerosol Fe deposition rates exerting a first-order control on NCP.

Boyd and Mackie (*4*) argue that uncertainties in simulated soluble Fe in aerosols are so large that one cannot use simulated soluble Fe deposition rates to infer a link between this property and NCP. We disagree, but first circumvent the question of the soluble Fe fraction by simply comparing NCP with simulated dust deposition. As one approach, we average individual rates of spring and summer NCP and climatological dust deposition within each zone (i.e., area between fronts) for the Australian, New Zealand, and South American sectors of the Southern Ocean. We observe a strong correlation between NCP and dust deposition (r^2 = 0.65, n = 15), supporting our earlier conclusion that dust deposition is an important control on NCP in the Southern Ocean. If we assume that 3.5% of dust is Fe, and 5% of that Fe is soluble (*5*–*7*), the derived Fe/C of sinking organic matter is 7.5 μmol mol^{-1}, again within the range of observations. Thus, a simple comparison between dust flux and NCP supports the importance of dust fluxes.

When regressing NCP and simulated dust and soluble Fe values averaged for each zone of the entire Southern Ocean, both climatological dust and soluble Fe deposition explain a large proportion of NCP variability (r^2 = 0.69 and 0.98, respectively).

Although the processes involved in atmospheric Fe dissolution are still not fully understood (*8*, *9*), the increase of Fe solubility with atmospheric transport time is now empirically well established (*8*, *10*). Our model of atmospheric iron solubilization is consistent with Baker and Jickells' (*8*) empirical relationship of iron solubility versus dust content derived from North and South Atlantic Ocean measurements (fig. S1). Hence, our conclusions would be similar had we used an empirical relationship and made no assumption about the mechanism of iron solubilization (and aerosol pH) instead of using a prognostic model. Furthermore, observed Fe solubilities vary symmetrically on both sides of the equator and are therefore inconsistent with differing interhemispheric atmospheric Fe chemistry (*11*).

Contrary to Boyd and Mackie (*4*), we believe that our model of atmospheric surface coating of aerosols with H_2SO_4, followed by Fe dissolution, is appropriate in both hemispheres (see SOM text). This view is reinforced by the absence of correlation between atmospheric concentration of acid species and iron solubility (*12*, *13*) (i.e., atmospheric acidity is saturating). Support comes from Luo *et al*. (*9*), who wrote that "in much of the atmosphere, cloud droplets may be acidic enough to process the iron, and that cloud processing is more important than predictions of acidity distributions." Certainly, H_2SO_4 from intense local pollution further enhances the acidity of aerosols (*14*).

Our modeled dust concentrations, dust deposition, and soluble Fe fraction in aerosols and precipitation are consistent with observations in the Southern and Northern Hemisphere [see table S1 and (*1*–*3*)]. This consistency validates the Fan *et al*. (*3*) model for our purpose: the large-scale statistical comparison between NCP and simulated soluble iron deposition at more than 350 sampling points. The predictions of our dust entrainment and transport model are also consistent with other models (e.g., *15*). To our knowledge, there are currently no direct observations of soluble Fe fluxes available for comparison to model predictions, and it seems unlikely that this property will be measured in the foreseeable future.

Boyd and Mackie assert that "there is little evidence, from an event-based analysis, of the biological impact of episodic dust storms in the waters south of both Australia and New Zealand." We noted (*1*) that our data alone do not allow one to distinguish whether synoptic (episodic) events or seasonal inputs of dust are responsible for the link between aerosol supply of Fe and NCP. The dominance of wet over dry oceanic deposition of dust [as shown by observations and captured by atmospheric models (*3*, *16*)] complicates the analysis of the biological response to episodic dust events. Episodic CO_2 drawdowns and enhanced biological activity have been hypothesized to be triggered by dust events (*17*, *18*). At the FeCycle site in the Subantarctic Zone southeast of New Zealand, Boyd *et al*. (*19*) conclude that the aeolian Fe supply is about 50 times as high as the oceanic supply of Fe.

Boyd and Mackie argue that the northward increase in NCP could be driven by "luxury uptake" (i.e., assimilation and storage of a non-limiting nutrient) of Fe south of the Antarctic polar front (APF) and by use of this stored Fe as phytoplankton are advected to the north. Several Fe enrichment experiments, both north and south of the APF, have demonstrated that the high-nutrient low-chlorophyll waters of the Southern Ocean are Fe limited (*20*). We agree that rapid zonal flows in the Southern Ocean produce chlorophyll plumes far downstream of island Fe sources (e.g., South Georgia). However, these results do not imply long-range northward transport by the slower meridional flows of the Ekman drift. Assuming northward transport of 38 Sv from upwelling around the APF (*21*) and a 40-m-deep mixed layer, the zonally averaged northward flow is around 4 cm s^{-1}. With a gross carbon specific growth rate of 0.1 d^{-1}, less than 5% of the original phytoplankton population at the APF remains 100 km to the north (e-folding of about 35 km). For comparison, our measurements extend equator-ward of the subtropical front, which sits, on average, more than 1600 km north of the APF (*22*). In addition, both Fe concentrations (*23*–*25*) and Fe sufficiency (*26*, *27*) generally increase at latitudes north of the APF. Hence, Fe in biomass derived from upwelling at the polar front is an unlikely explanation for the northward increase in NCP.

Boyd and Mackie further assert that marine organisms strip additional lithogenic Fe from

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dust (*28*). This process will substantially modify the stoichiometric relationship we envisioned but strengthens the link between dust and NCP. Their suggestion that continental shelves are important Fe sources to open ocean waters has merit, deserves further study, and can help account for our observation of high NCP at the northern bound of the Southern Ocean. However, recent evidence suggests that the meridional extent of shelves' impact on dissolved iron concentration could be limited (*29*). Any differences in remineralization depth scales between Fe and C are undoubtedly important but in no way negate our conclusions. Finally, we never claimed, and do not believe, that "high productivity is driven solely by dust supply downstream of Patagonia, Australia, New Zealand, and South Africa" (*4*).

We agree with Boyd and Mackie that there is a strong need for a better understanding of Fe biogeochemistry in the Southern Ocean through more extensive observations (including soluble fraction in aerosols, aerosol acidity, soluble Fe deposition from snow and rain, and surface ocean measurements) and improved and empirically tested atmospheric transport and oceanic biogeochemistry models. Several studies [cited in (*1*)] have clearly demonstrated that there are a multitude of Fe sources in the Southern Ocean. Our study supports aerosol Fe as one important control on NCP over broad reaches of the Southern Ocean.

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Supporting Online Material

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SOM Text
Fig. S1
Table S1
References

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